OBSERVATIONS OF VERTICAL WINDS AND THE ORIGIN OF THERMOSPHERIC GRAVITY WAVES LAUNCHED BY AURORAL SUBSTORMS AND WESTWARD TRAVELLING SURGES

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Several sequences of observations of strong vertical winds in the upper thermosphere will be discussed in this paper, in conjunction with models of the generation of such winds. In the auroral oval, the strongest upward winds are observed in or close to regions of intense auroral precipitation and strong ionospheric currents. The strongest winds, of the order of 100 to 200 m/sec are usually upward, and are both localized and of relatively short duration (10 to 20 min). In regions adjacent to those displaying strong upward winds, and following periods of upward winds, downward winds of rather lower magnitude (40 to about 80 m/sec) may be observed. Strong and rapid changes of horizontal winds are correlated with these rapid vertical wind variations. Considered from a large scale viewpoint, this class of strongly time-dependent winds propagate globally, and may be considered to be gravity waves launched from an auroral source. During periods of very disturbed geomagnetic activity, there may be regions within and close to the auroral oval where systematic vertical winds (upward or downward) of the order of 50 m/sec will occur for periods of several hours. Such persistent winds are part of a very strong large scale horizontal wind circulation set up in the polar regions during a major geomagnetic disturbance. This second class of strong horizontal and vertical winds corresponds more to a standing wave than to a gravity wave, and it is not as effective as the first class in generating large scale propagating gravity waves and correlated horizontal and vertical oscillations. A third class of significant (10 to 30 m/sec) vertical winds can be associated with systematic features of the average geomagnetic energy and momentum input to the polar thermosphere, and appear in statistical studies of the average vertical wind as a function of Universal Time at a given location.

INTRODUCTION

Recent papers by Hernandez[1], Meriwether et al[2], and Rees et al[3, 4] have described the observation of significant (20 to 150 m/sec) vertical winds from mid-latitude[1] and from high (auroral) latitude stations[2, 3, 4], using ground-based Fabry-perot interferometers to observe the thermospheric OI 630 nm emission line. Spencer et al[5, 6] have observed similar vertical wind magnitudes in-situ from their satellite-borne WATS (Wind and Temperature Sensor) instruments on Atmospheric Explorer and on Dynamics Explorer.

Such wind magnitudes are at least one order of magnitude larger than the systematic vertical winds (3 -5 m/sec) which can be associated with the diurnal 'breathing' of the thermosphere[7, 8] at upper thermospheric levels (300 to 400 km) in response to solar UV and EUV heating at middle and low latitudes. Generally, the observations of strong vertical winds indicate that there is a rapid

time-variation of such winds, and that the horizontal scale of the regions of strongest upward and downward flow is also relatively limited, of the order of 100 to a few hundred km.

The observations indicate that the strong vertical winds are the result of intense excitation of the middle and upper thermosphere. The source is strong, localized and may vary rapidly with time. Correlated horizontal and vertical wind changes[1, 3] suggest that, after the initial excitation, the propagation of the wind disturbance follows the natural thermospheric response to strong excitation, a form of gravity wave propagation, where the disturbances may propagate throughout the entire global thermosphere.

RESUME OF OBSERVATIONS

The most frequently observed class of strong (> 50 m/sec) vertical wind disturbance[3] is associated with auroral substorms and westward-travelling-surges, and similar energetic auroral phenomena. On examining the data from several hundred nights when observations of thermospheric winds are available from Kiruna Geophysical Institute (67 N, 22 E geographic), a location within the auroral oval, it would appear that such disturbances are observed, on average, about one in two or three nights of clear sky observations, for the geomagnetic activity conditions of the period late 1980 to late 1983.

The observations indicate that when any substorm or westward travelling surge occurs equatorward of the observing station, or propagates from equatorward to overhead, strong upward vertical winds will be observed immediately prior to the arrival of the surge or substorm, as seen in the auroral emissions (particularly in OI 630 nm). Associated with the strong upward winds is an outward explosion of the horizontal winds.

There is a high degree of correlation between the vertical and horizontal wind changes, which will be described in reference to three particular examples. Events which occur poleward of the observing station create similar changes of the horizontal wind, and although the vertical wind changes are not usually observed as clearly for such events, this has to be purely a result of less favourable observing geometry.

I. Nov 23/24 1982

Figure 1 shows the combined horizontal and vertical wind observations from KGI during the night of Nov 23/24 1982. There was a major substorm and westward travelling surge about 19 UT, which propagated toward and overhead Kiruna from the southeast. This propagation can be inferred from the OI 630 nm intensity observations. Following a general increase in the magnitude of westward and equatorward winds between 18.00 UT and about 18:40 UT, there was an short-lived period of extremely strong upward winds (up to 165 m/sec) starting about 18.50 UT, which coincided with a sudden reversal in the meridional wind as observed to the north of Kiruna.

Note: all of the observations of the 'horizontal' winds were made at a zenith distance of 60 degrees. For a mean emission altitude of 240 km, this observing region is some 400 km away from Kiruna along the specific viewing direction.

After 19.20, the strong upward vertical winds subsided, and the meridional wind, to the north of Kiruna, reverted to a strong equatorward value (400 m/sec). The degree of correlation between changes in the various wind components, and the nature of the 'outward explosion' of the winds during the disturbance is illustrated further in Figure 2. There were at least two surges of the equatorward wind observed to the south of Kiruna, during the period 19.00 to 20.30 UT, which could be associated with this period of intense auroral activity.

Later in the night, up to midnight UT, there were several significant fluctuations of the vertical wind, of the order of 50 m/sec. These fluctuations are difficult to relate to local auroral activity, and may reflect the propagation of waves from more distant auroral disturbances.

II. Feb. 4/5 1983

Wind observations during a second disturbed night (Feb 4/5 1983) are shown in Figure 3. There were several fluctuations of the vertical wind up to about 20 UT, and then there was a short period of violent (150 m/sec) upward wind centered about 21 UT. Immediately before and after the period of strongest upward winds, there was a short period of 50 m/sec downward winds. As with the wind observations of the Nov 23/24 period, there was again a strong reduction of the equatorward wind observed to the north of Kiruna during the period around that when the strongest upward winds occurred.

A significant feature of the auroral activity of both these periods was that the auroral activity was mainly equatorward of Kiruna.

III. Dec. 7/8 1982

To contrast with observations which are typical of strong events where the main auroral and electrojet activity occurs equatorward of Kiruna, the data obtained on Dec. 7/8 1982 will be shown. Between 19.00 and 20.00 UT, the wind component observed in the northwest direction changed by about 600 m/sec, with rather smaller changes in all other directions. The vertical wind during this event was, however, strongly downward (50 m/sec). The main auroral activity and the centre of the auroral electrojet were north of Kiruna.

This difference in location of the main auroral activity relative to Kiruna explains the different vertical wind behaviour which was observed caused by the two rather similar geomagnetic events. The comparison of the two events also defines the spatial extent of the region of strong upward winds rather well.

When the major region of heating is overhead or to the north (poleward) of Kiruna, by perhaps 200 km, the equatorward and poleward wind explosion is observed. This is associated with a region of downward winds overhead Kiruna, as the atmosphere relaxes on leaving the region of intense heating. When the strong heating is about 200 km equatorward of Kiruna, rather than directly overhead or poleward, the effects of the heating in driving upward and poleward winds are directly observable.

Part of the explanation is due to the combination of the observing geometry and the geometry of the earth's magnetic field. OI 630 nm is generated from regions (200 to 300 km) which are significantly higher than those where the particle and frictional heating maximises during auroral substorms (120 to 160 km). The region of maximum heating would thus be expected to be somewhat poleward ($\sim$50 km) of the region of maximum OI 630 nm emission, assuming that they were related. In practice, it might appear from some of the time-variations observed in OI 630 nm and the wind variations that the regions of highest heating were rather further poleward (100-200 km) of the maximum OI 630 nm emissions.

From the auroral intensity data obtained during these rather representative events, the latitudinal extent of the regions generating the strongest upward winds appeared to be about 200 km. The longitudinal extent is probably of the order of 1000 km, but will be related to the specific morphology of a given auroral event.

PERIODS OF SYSTEMATIC LARGE VERTICAL WINDS DURING MAJOR GEOMAGNETIC DISTURBANCES

In Figure 5, some of the wind observations made from Kiruna during the afternoon of Dec. 17 1982 are shown. Very fast westward winds occurred during the early part of the afternoon, peaking in excess of 900 m/sec, mainly westward and northwestward in direction. Throughout the period from 13:30 UT to 17:00 UT (3.5 hours), there was a mean downward vertical wind of the order of 50 m/sec. Kiruna was located on the poleward side of the main part of the greatly expanded auroral oval during this extremely disturbed period. The combination of extremely rapid westward winds, driven[9] by ion drag in the auroral oval, and downward winds appear to be part of a form of standing wave, with the atmosphere relaxing as it leaves a region of intense acceleration and heating (the dusk auroral oval).

Systematic mean vertical winds of the order of 10 to 20 m/sec have also been found[3] in statistical analyses of many days of thermospheric wind observations from both Skibotn (Norway) and Svalbard (Spitzbergen, 16 E 79 N). These mean vertical winds appear to be consistent and reproducible signatures of the geomagnetic forcing of the auroral and polar thermosphere, and are distinct from the strong time-dependent winds discussed above.

THEORETICAL EXPLANATION AND SIMULATION OF INTENSE VERTICAL WINDS

Figure 6 displays the simulated horizontal (vector) and vertical (scalar) wind component distributions over the northern, winter, polar region during a period of relatively quiet geomagnetic conditions. This is a quasi-steady state simulation, the only time-dependence being due to the rotation of the earth, carrying the offset geomagnetic polar regions around the geographic poles, and thus varying the location, and solar photo-ionisation and insolation, of the geomagnetic polar regions as a function of UT.

There is weak upwelling at low and middle latitudes on the dayside, and weak downwelling on the nightside at middle latitudes, except for a small, post-midnight, region of weak upwelling associated with the 'post-midnight bulge', and its temperature/thermospheric wind anomaly. The geomagnetic polar region contains regions of significant upwelling (3 to 10 m/sec) around the boundaries of the auroral oval, and over the central polar cap. There are also regions of weak downwelling in the poleward boundaries of the dusk and dawn parts of the auroral oval.

In Figure 7, the horizontal and vertical wind distribution is shown for a second quasi-steady state simulation which uses a geomagnetic input within the polar regions[4] corresponding to moderately disturbed conditions ($Kp \sim 4$). Upward wind velocities are considerably enhanced, with peak values of the order of 40 m/sec in the dayside cusp. Regions of moderate downward winds (10 m/sec) border the regions of upwelling. The peak upward winds of 40 m/sec in the dayside cusp are generated by a combination of convergence from the dusk and dawn auroral oval, frictional heating within the dayside auroral oval, and a soft 'cusp' electron source of the order of 4 ergs/cm^2.

Figures 8, 9 and 10 show, with the same presentation as Figures 6 and 7, the circulation changes which develop during a simulated geomagnetic (auroral) substorm[4] in the region near magnetic midnight.

The simulated disturbance is started at 20.4 UT (Figure 8), with a large input of energy into a limited region of the auroral oval close to magnetic midnight. There is an immediate response in the vertical wind, with upward velocities of the order of 200 m/sec throughout the region where the peak energy input (100 ergs/cm^2) has been dumped. Horizontal wind changes occur with a

slight delay, but within 30 min (at 20.9 UT, Figure 9), there is a major expansion of the atmosphere horizontally, as well as vertically, away from the region of intense energy input. The equatorward and poleward wind surges generated by the large input can be easily seen propagating away from the vicinity of the simulated substorm. Large equatorward winds have reached a latitude of 50 degrees in the midnight region, from their source latitude of 70 degrees, withinn 30 min of the substorm onset.

The major 'substorm' source of energy is cut off at 20.9 UT, allowing a recovery from the disturbance. By 21.6 UT (Figure 10), the wind distribution within the polar cap and auroral oval has returned to a state close to the initial state. However, at lower geomagnetic latitudes, large wind disturbances continue to propagate equatorward for several more hours. By 21.6 UT, the disturbances have reached 30 degrees latitude, and within a further hour (2.2 hours after onset), the propagating waves from the northern polar region meet with those generated in the southern hemisphere near the equator.

Figures 9 and 10 display the extent to which these propagating waves have correlated vertical and horizontal wind oscillations. At a particular mid-latitude ground-based station, the vertical and horizontal winds will both oscillate quasi-periodically as the series of gravity waves propagate past the station.

The wind disturbances set up by a single geomagnetic pulse, with a simple geometrical and time-dependent variation of the geomagnetic energy inputs, are quite complex, and there is also a complicated local time/longitudinal structure. The simulated disturbances correspond quite well to the time-dependent observations reported[1, 3], and have many of the features of the theoretical gravity waves which have been generated in previous linear two-dimensional models.

During extremely disturbed periods, the auroral oval expands equatorward, there is a considerable increase in the cross-polar cap electric potential, and the total deposition of geomagnetic energy in both polar regions may exceed 10^{12} watts. The effects of such conditions on the thermosphere can be estimated from Figure 11, which is taken from a simulation generated to correspond to an event observed on Dec 12 1981. This event was qualitatively similar to the one observed on Dec 17 1982, described previously.

Extremely large sunward horizontal winds occur in the dusk and dawn parts of the auroral oval, particularly in the dusk oval (near 1 km/sec), and there are also strong anti-sunward winds of close to 800 m/sec over much of the polar cap. The vertical winds generated under such conditions are qualitatively similar to those shown in Figure 7, but with a factor of 2 to 4 increase in magnitude. For example, the downward winds of 10 m/sec which occur on the poleward boundary of the dusk auroral oval are increased to about 40 to 60 m/sec. It would appear that this is the simplest mechanism which can account for the persistent 50 m/sec downward winds observed from Kiruna during the disturbance of Dec 17 1982. The persistent downward winds exist as a 'standing wave', where the atmosphere is relaxing after intense acceleration and heating in the dusk auroral oval.

Under less disturbed conditions, the persistent diurnal variation of vertical wind behavior observed at polar and auroral locations can also be explained in a similar way. There is considerable day to day variation in this behaviour, which can be related to the complex time-dependent variations of individual geomagnetic disturbances.

SUMMARY

Vertical winds of the order of 5 to 10 m/sec or larger are a persistent feature of the polar upper thermosphere. The signature of geomagnetic heating of the upper thermosphere under relatively quite geomagnetic conditions can explain average upward and downward winds of such

magnitudes which are observed in systematic studies. Such magnitudes exceed the average diurnal variations associated with the thermospheric 'breathing' in response to solar UV and EUV heating at low and middle latitudes.

Violent excursions of the vertical wind, of short duration, typically 10 to 20 min, where upward velocities of 200 m/sec may be observed at times, and with large correlated changes of the horizontal wind, can be associated with intense auroral substorms and similar energetic events (Westward Travelling Surges, etc). Such events generate a localized explosion of the upper themosphere. Away from the source region, the propagating waves from such events are essentially the thermospheric gravity waves launched from an auroral source. These waves propagate globally, and leave the mid-latitude thermosphere 'ringing' for many hours, as the gravity waves propagating form both hemispheres interact. During periods of moderate to intense geomagnetic activity, the wave patterns may become so complex that it is impossible to identify individual disturbances by their correlated horizontal and vertical wind changes (10 to 30 m/sec at mid-latitudes, rather than the 100 m/sec observed at auroral latitudes).

During extremely disturbed periods, standing waves may be generated, with embedded regions of large (upward and downward) vertical winds (50 m/sec), associated with, or adjacent to, regions of horizontal winds of the order of 500 m/sec. Although these may be the signature of the deposition of intense geomagnetic heating of the thermosphere, their long duration, sometimes exceeding 4 to 6 hours, implies that they are less efficient generators of gravity waves than the source associated with auroral substorms in the magnetic midnight region.

It is not possible to identify from the FPI observations alone the combination of heating sources which contribute to generating the strong vertical winds. The 3-D T-D model allows various mixes of heat sources to be tested. If the source were kilo-volt auroral electrons, a deposition rate in excess of 100 erg/cm^2/sec would be required to explain 100 m/sec upward winds (with the 10 min observed duration). Satellite observations of precipitation include such values, but probably too rarely to explain the frequency of strong upward vertical winds.

A significant or large contribution from supra-thermal or low energy electrons would decrease the demand on total energy input considerably, since these electrons heat the thermosphere at levels where the generation of large vertical winds is more efficient (per unit energy deposition rate).

There are objections to this source as a sole generator of strong vertical winds. Firstly, even modest (10 – 20 ergs/cm^2/sec) of 5 to 10 ev electrons require very large number fluxes of electrons, which may not be consistent with potential source regions. Secondly, there is little supporting data from satellite or ground-based auroral morphology studies. In particular, the FPI itself tends to observe the largest vertical winds in regions which are poleward, but immediately adjacent, to regions where the substorm- or surge-associated enhancement of OI 630 nm emission occurs.

A third contributor to the energy requirements could be intense frictional and Joule heating in the region of, and immediately adjacent to, the substorm- and surge activity. Intense field-aligned currents are known, from recent satellite observations, to complete the magnetospheric circuit associated with substorm and surge current systems in adjacent regions which are not strongly excited by auroral precipitation. The strong horizontal currents required to complete the circuit of upward and downward field-aligned currents have to flow through regions where the ionospheric conductivity is not particularly enhanced. This implies that the Joule and frictional heating rates might be quite intense, and a valuable contributor to the total heating demanded by the observed strong vertical winds. Measurements of the state of the ionosphere, and its current and electric field systems, in regions adjacent to substorms and surges have, as yet, provided rather inadequate

results to fully test and complete the menu of geomagnetic heat sources contributing to these violent and rather fascinating wind disturbances.

Acknowledgements

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REFERENCES

1. HERNANDEZ, G. (1982) Vertical motions of the neutral thermosphere at midlatitude. Geophys. Res. Lett. 9, 555.
2. MERIWETHER, J. (1983) Private Communication.
3. REES, D., SMITH, R. W., CHARLTON, P. J., MCCORMAD, F. G., LLOYD, N., and AKE STEEN. The generation of vertical thermospheric winds and gravity waves at auroral latitudes-I. Observations of vertical winds. Planet. and Sp. Sci. 32, 667-684.
4. REES, D., SMITH, M. F., and GORDON, R. The generation of vertical thermospheric winds and gravity waves at auroral latitudes-II. Theory and numerical modelling of vertical winds. Planet and Sp. Sci. 32, 685-705.
5. SPENCER, N. W., THEIS, R. F., WHARTON, L. E. and CARIGNAN, G. (1976) Local vertical motions and kinetic temperature from AE—C as evidence for aurora-induced gravity waves. Geophys. Res. Lett. 3,313.
6. SPENCER, N. W., WHARTON, L. E., CARIGNAN, G. and MAURER, J., (1982) Thermosphere zonal winds, vertical motions and temperature as measured for Dynamics Explorer. Geophys. Res. Lett. 9, 953.
7. GEISLER, J. E. and DICKINSON, R. E. (1968) Vertical motions and nitric oxide in the upper mesosphere. J. atmos. terr. Phys. 30, 1505.
8. HERNANDEZ, G. and ROBLE, R. G., (1979) On divergences of the thermospheric meridional winds at midlatitudes. Geophys. Res. Lett. 6, 294.
9. REES, D., FULLER-ROWELL, T. J., SMITH, M. F., GORDON, R., KILLEEN, T. L., HAYS, P. B., SPENCER, N. W., WHARTON, L. and MAYNARD, N. C. (1985). The Westward jetstream of the evening auroral oval (accepted by Planet. and Sp. Sci.)

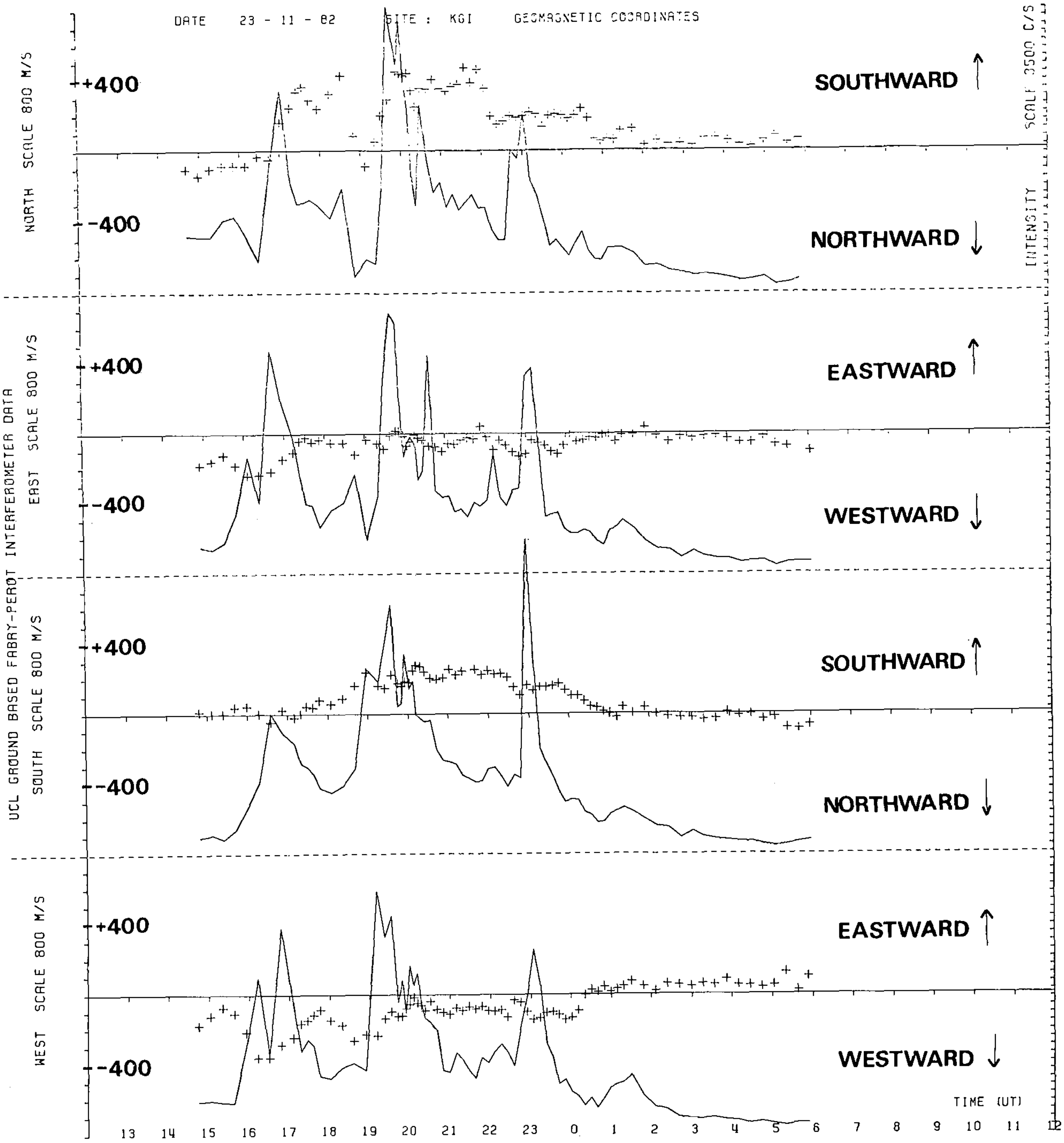
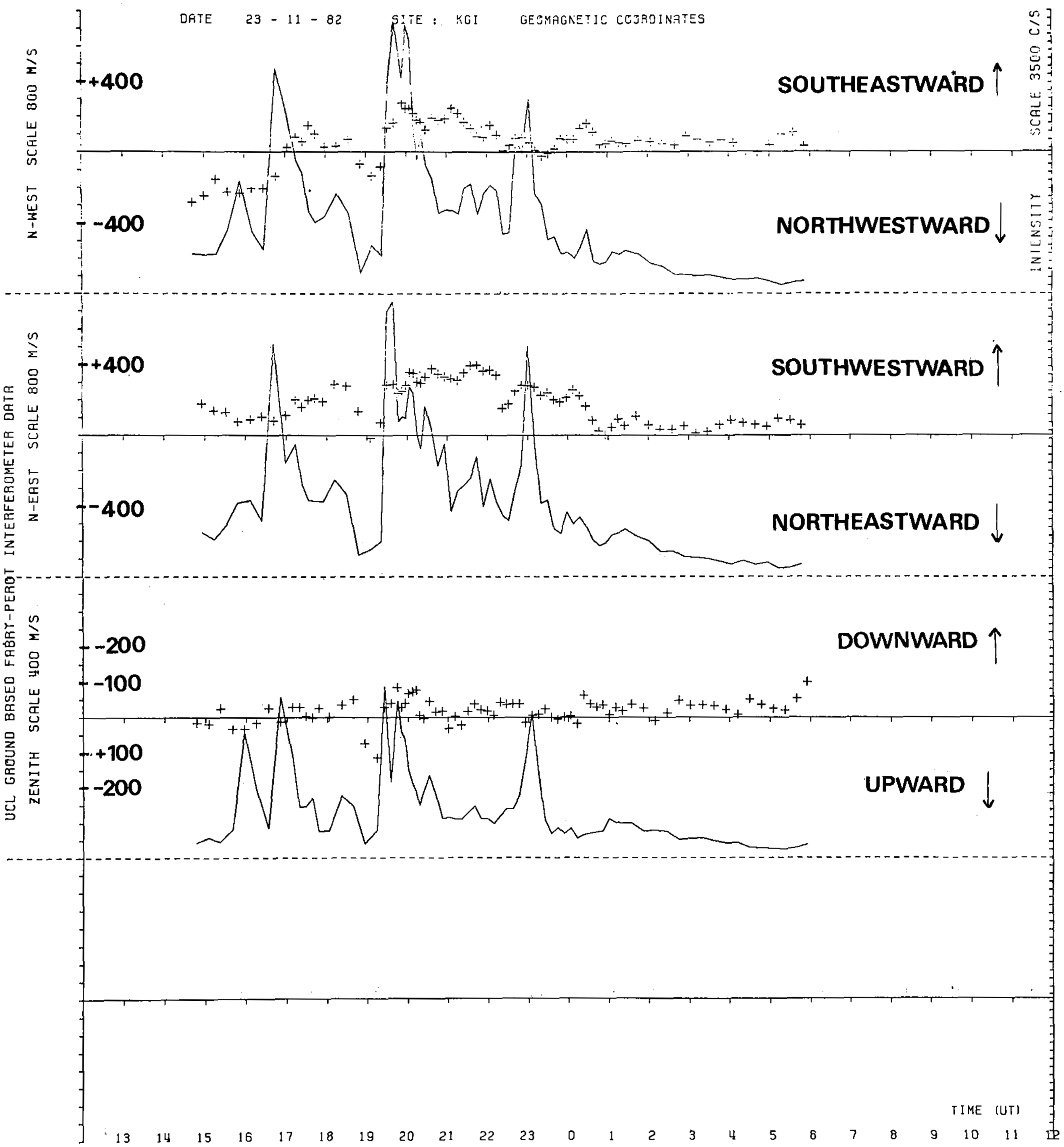


Figure 1a. Thermospheric wind observations in the N, NE, E, S, W, NW and Vertical Directions from the FPI at Kiruna Geophysical Institute on the night of 23/24 Nov 1982. The major focus of interest is the correspondence between changes observed in each of the viewing directions in the period 18.00 to 20.00 UT before, during and after the strong geomagnetic disturbances around 19.00 UT. Observed winds are indicated by the crosses (+), and the OI 630 nm emission intensity by the continuous line.



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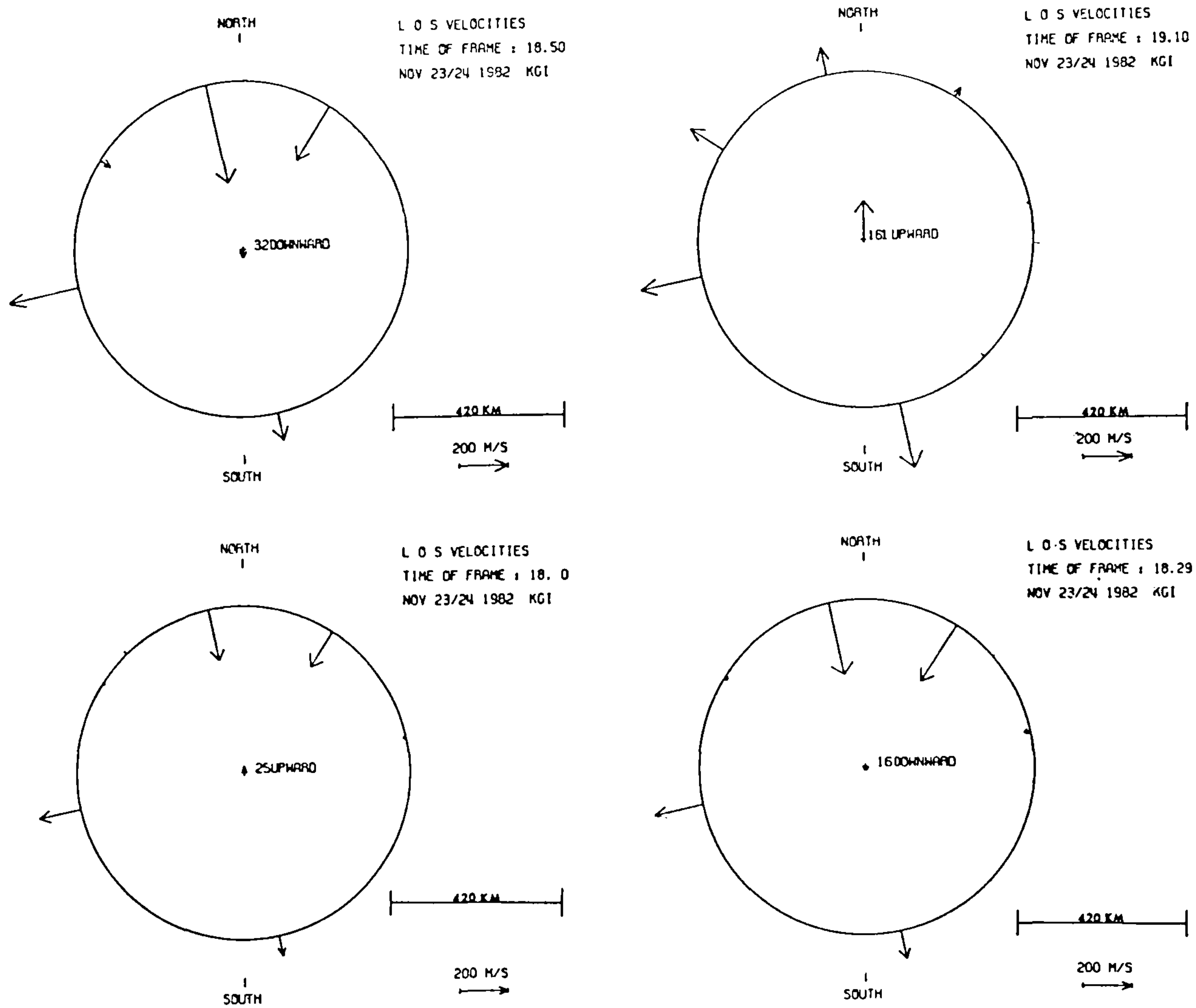
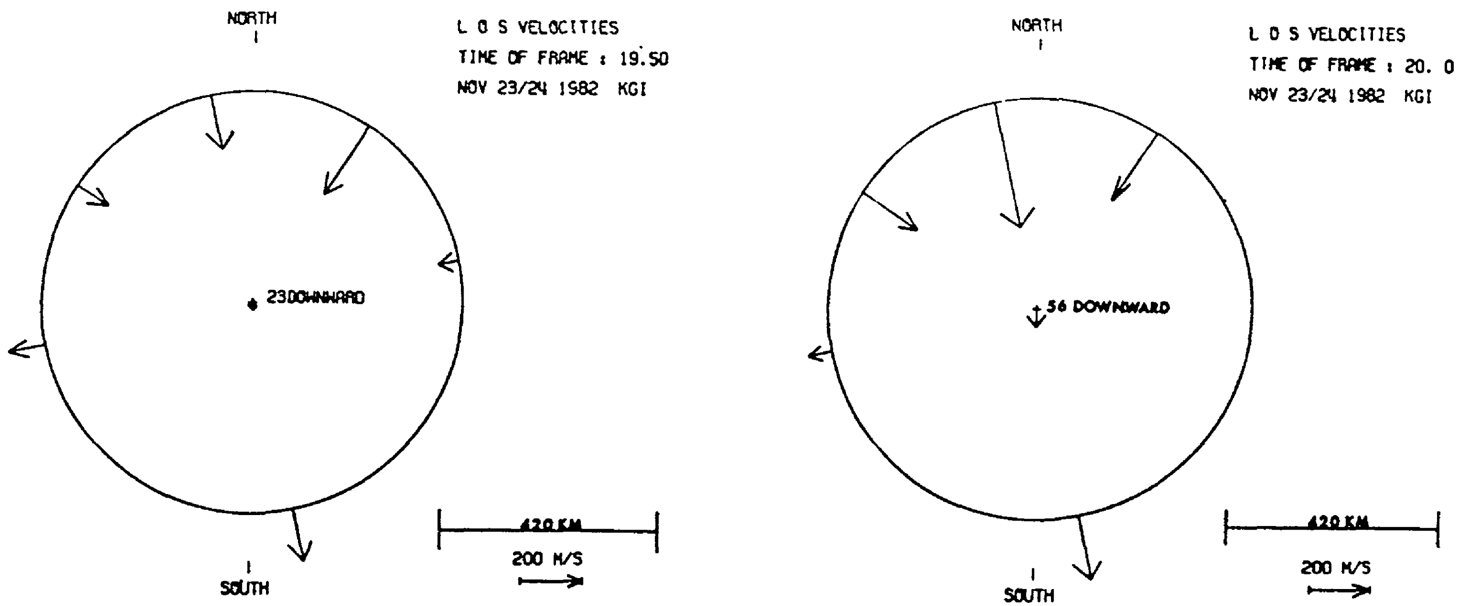


Figure 2a. Thermospheric wind observations in the N, NE, E, S, W, NW and Vertical Directions from the FPI at Kiruna Geophysical Institute on the night of 23/24 Nov 1982. The period 18.00 to 20.00 UT before, during and after the strong geomagnetic disturbances around 19.00 UT is examined in detail, with the instantaneous wind distribution being shown at times between 18.00 and 20.00 UT, to place the vertical winds in the context of the horizontal circulation.



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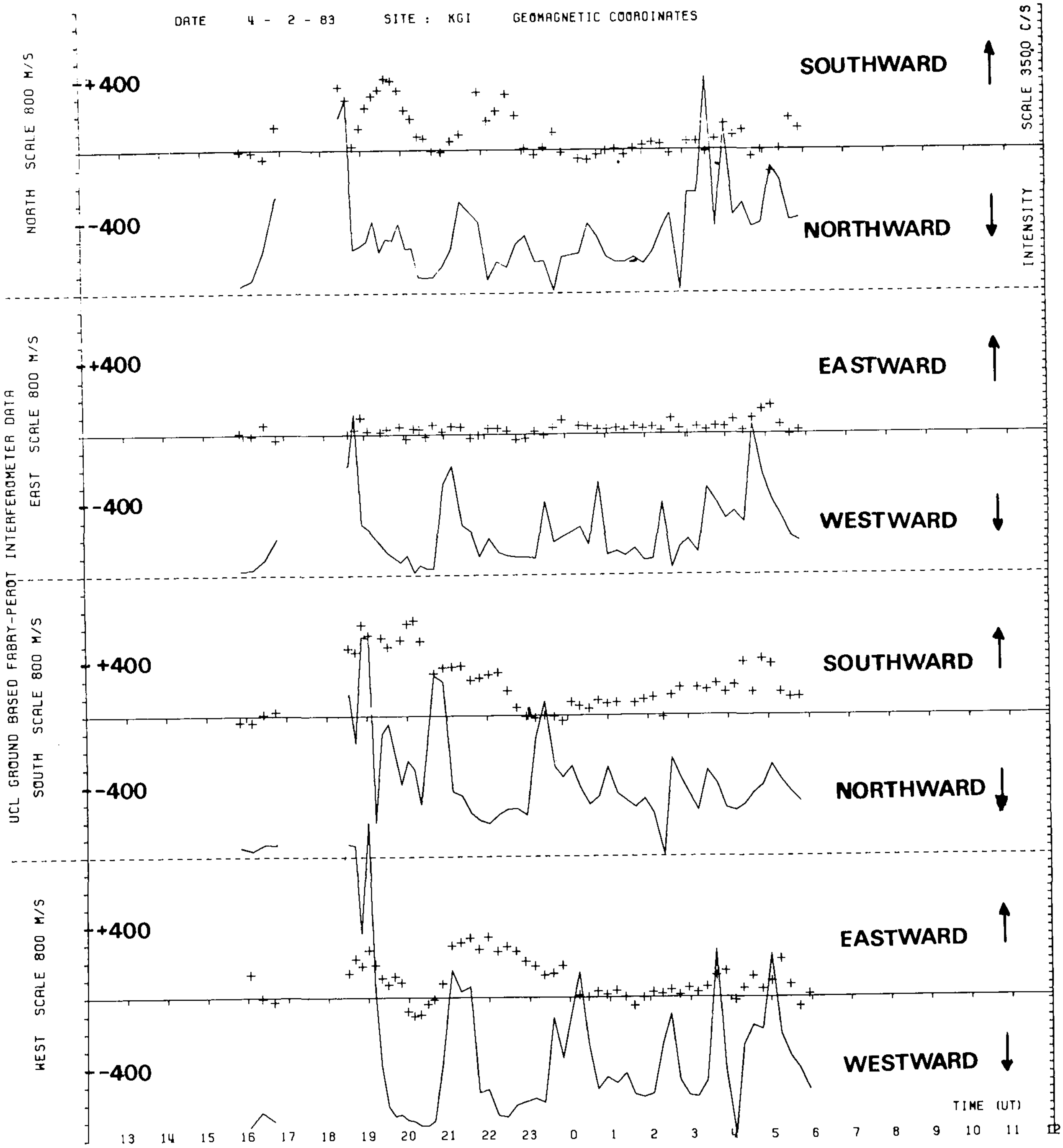
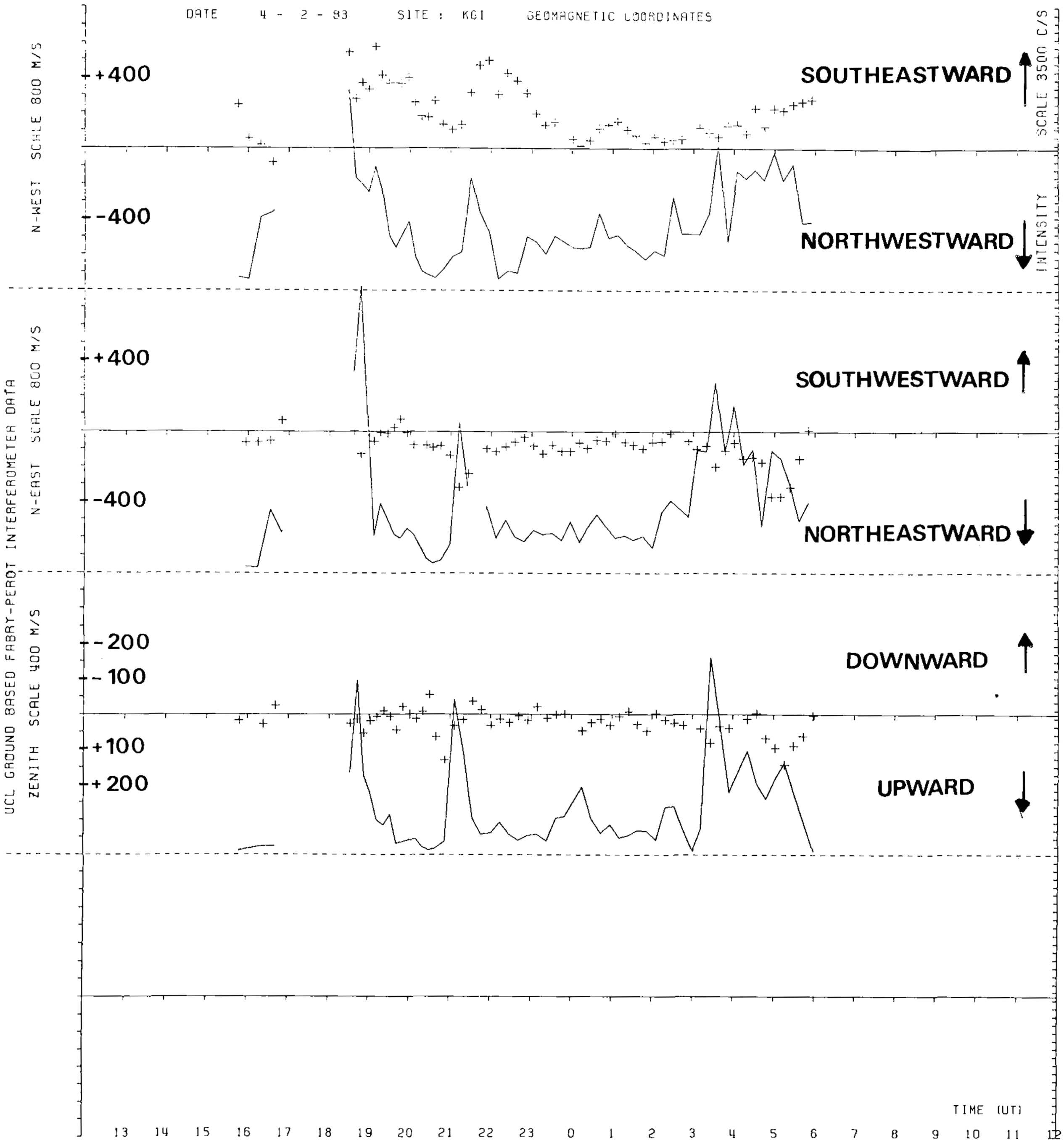


Figure 3a. Thermospheric wind observations in the N, NE, E, S, W, NW and Vertical Directions from the FPI at Kiruna Geophysical Institute on the night of 4/5 Feb 1983. The major focus of interest is the correspondence between changes observed in each of the viewing directions near the strong geomagnetic disturbance around 21.00 UT. There was a 'great red' aurora between 17.00 and 18.00 UT. Observed winds are indicated by the crosses (+), and the OI 630 nm emission intensity by the continuous line.



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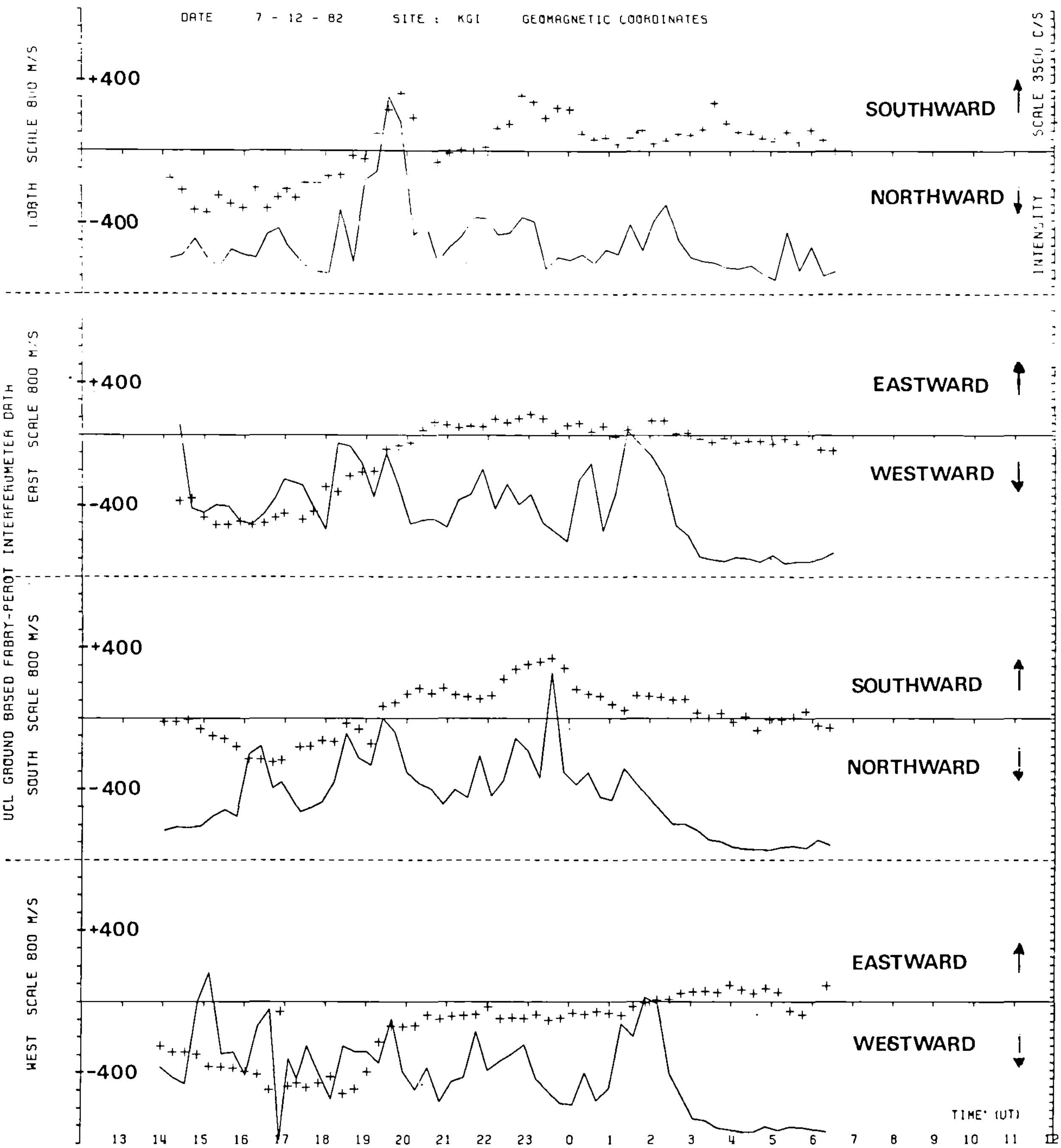
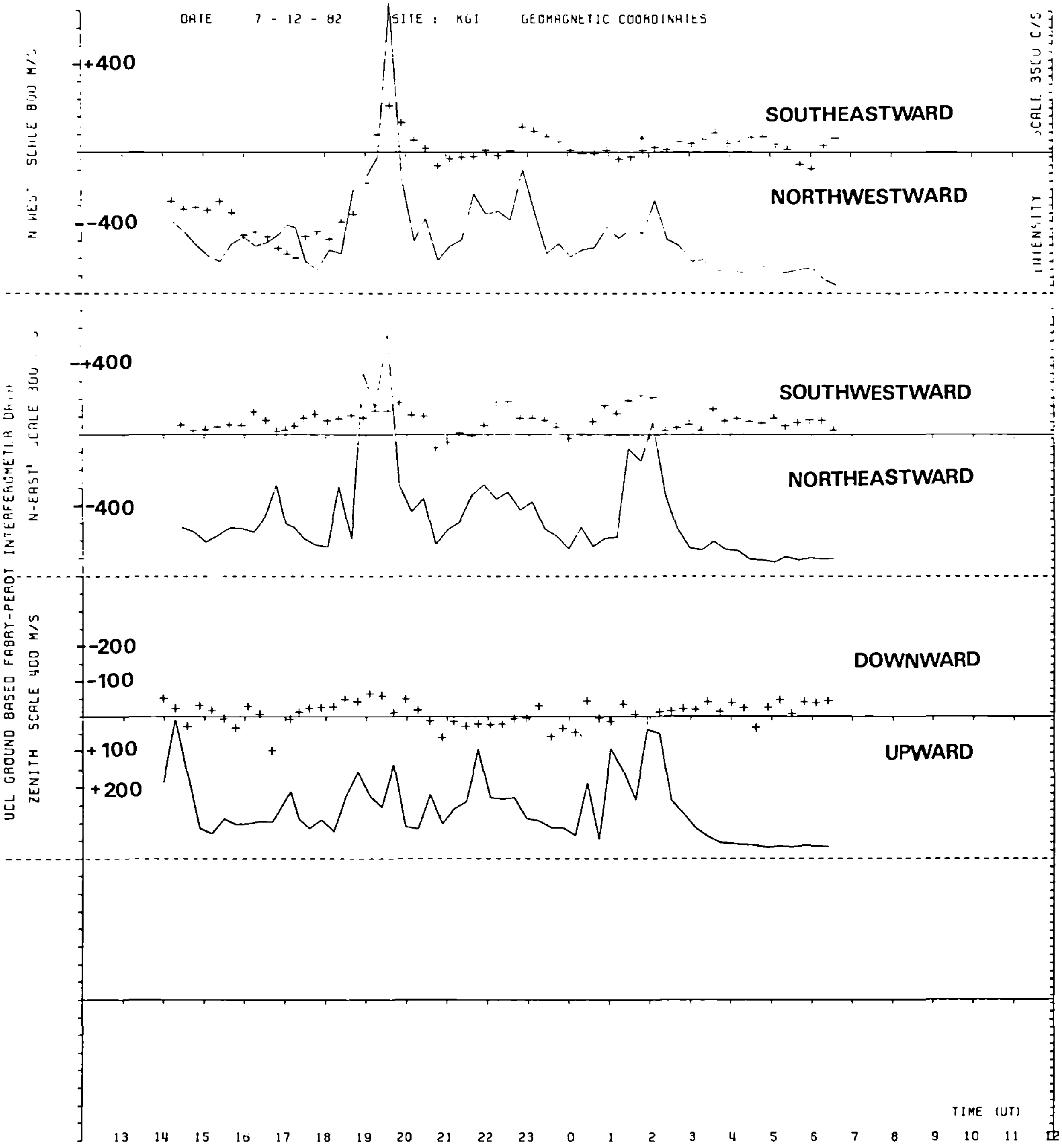


Figure 4a. Thermospheric wind observations in the N, NE, E, S, W, NW and Vertical Directions from the FPI at Kiruna Geophysical Institute on the night of 7/8 Dec 1983. The major focus of interest is the correspondence between changes observed in each of the viewing directions in the period 18.00 to 20.00 UT before, during and after the strong geomagnetic disturbances around 19.00 UT. Observed winds are indicated by the crosses (+), and the OI 630 nm emission intensity by the continuous line.



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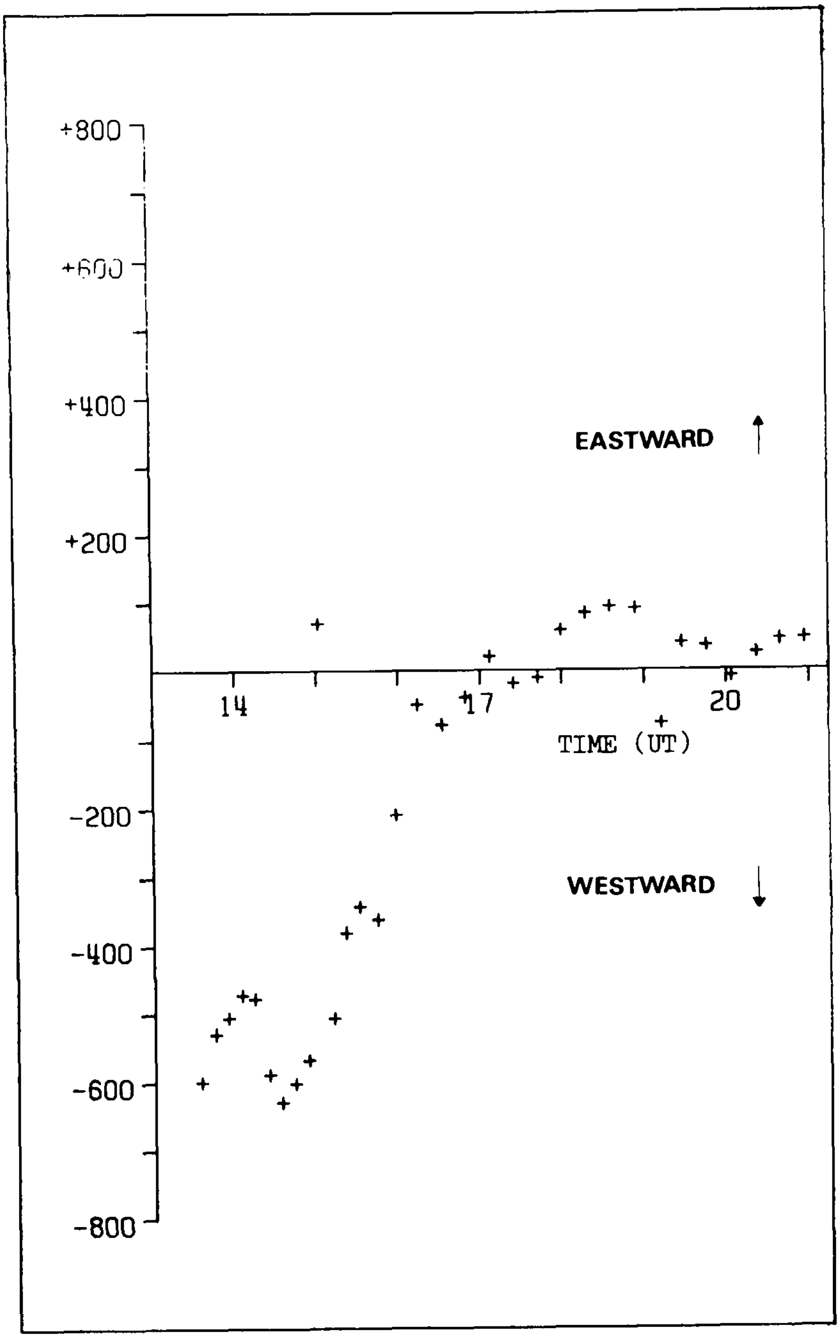
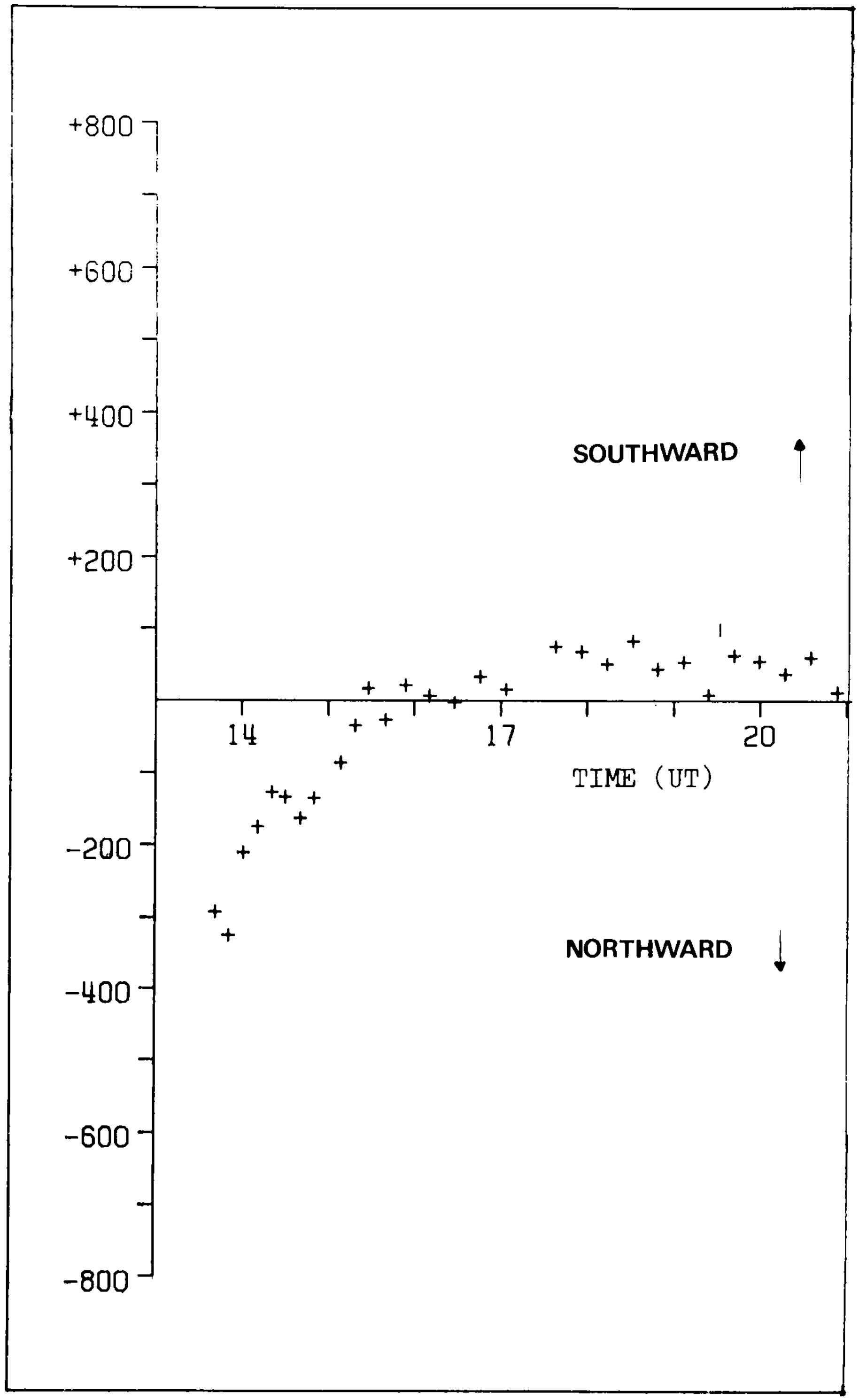


Figure 5a. Thermospheric wind observations in the West, North, Northwest and Vertical Directions from the FPI at Kiruna Geophysical Institute on the night of 17 Dec. 1982. The major focus of interest is the correspondence between the strong westward winds in the period 13.30 to 16.00 UT during the major geomagnetic disturbances which started at 08.00 UT. Observed winds are indicated by the crosses (+).



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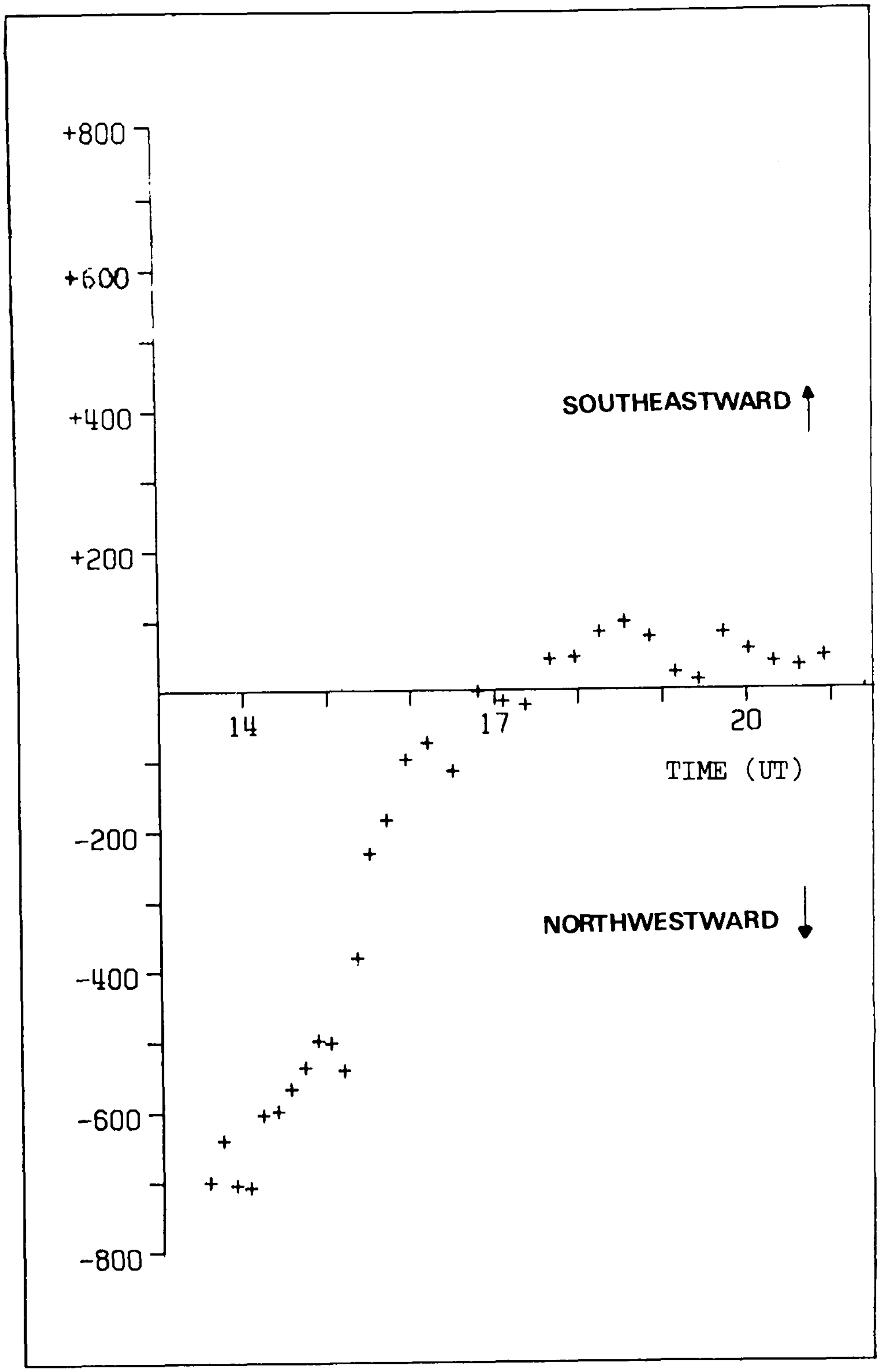

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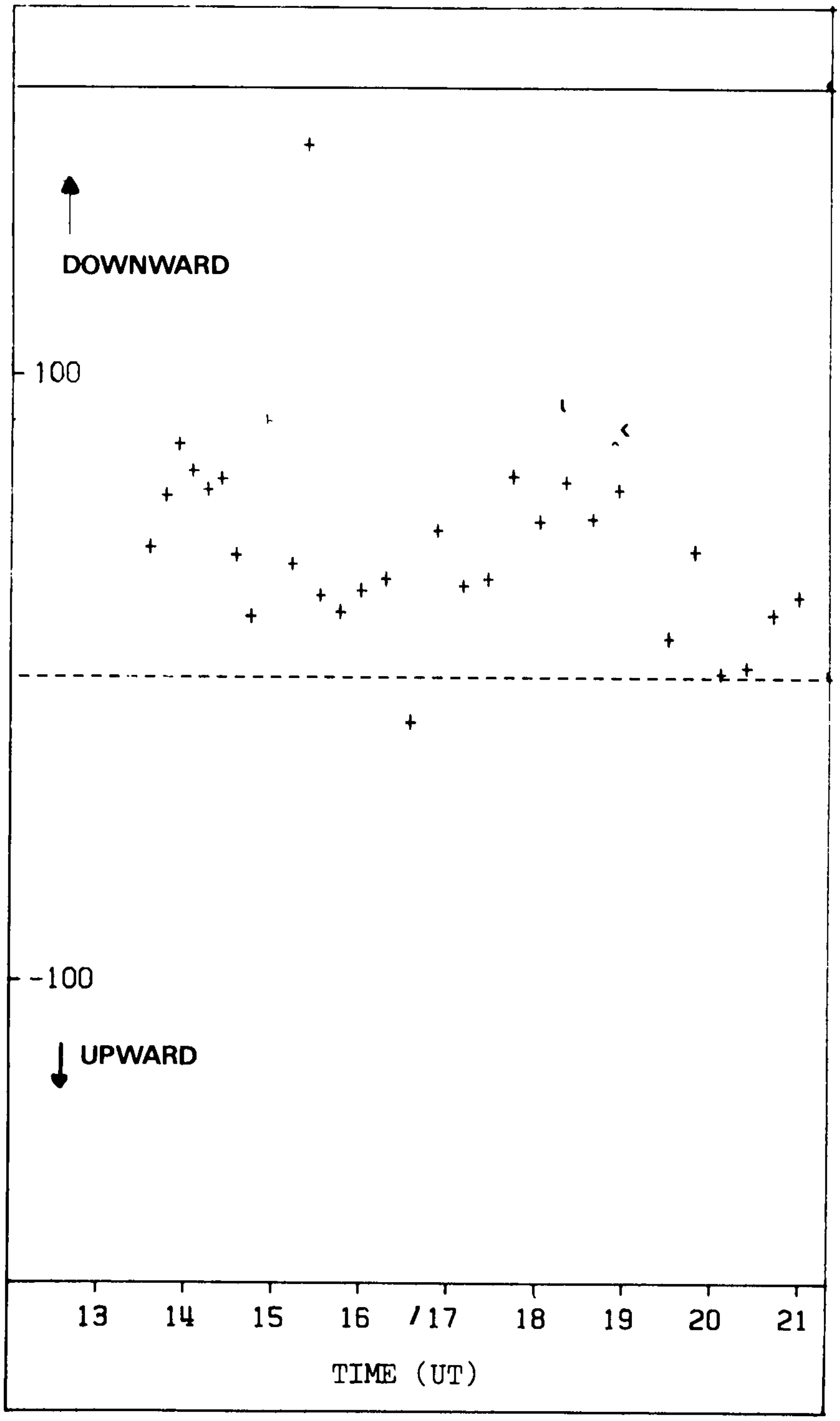

Figure 5d. Figure 5 continued.

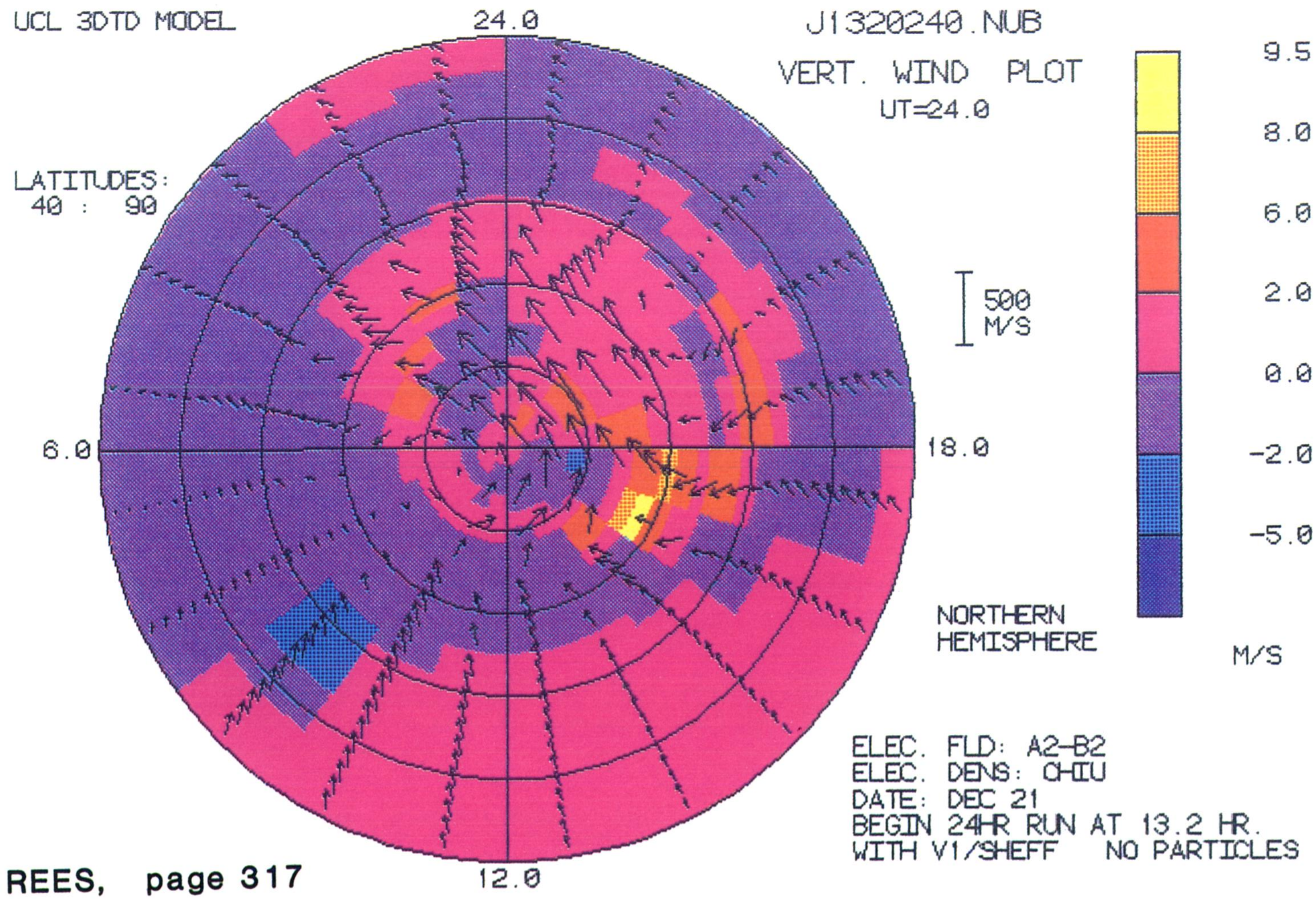

Figure 6. Vertical and Horizontal wind distributions over the Northern Polar region for relatively quiet geomagnetic conditions. Even at a low level of geomagnetic energy and momentum input, there are upward winds over much of the winter auroral oval and polar cap regions. At lower latitudes, the upward winds of the dayside, and the downward winds of the nightside, can be observed. The magnitudes of these mid-latitude winds are less than 5 m/sec at 320 km.

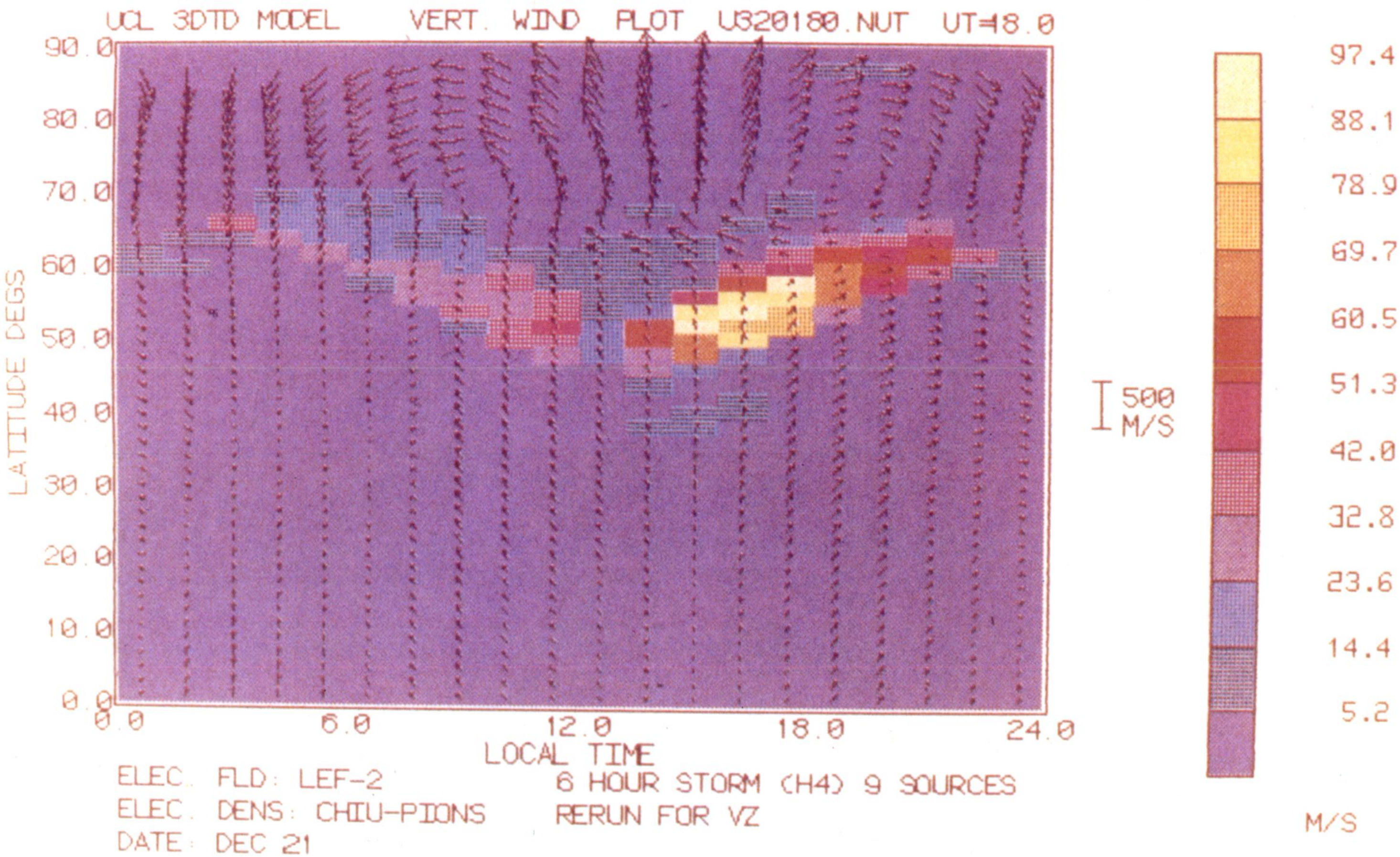

Figure 7. Vertical and Horizontal wind distributions over the Northern Polar region for rather disturbed geomagnetic conditions. Upward winds of 40 m/sec occur in the dayside polar cusp region, where there is strong convergence and 'soft' particile heating. There are upward winds of 5 to 20 m/sec around much of the auroral oval.

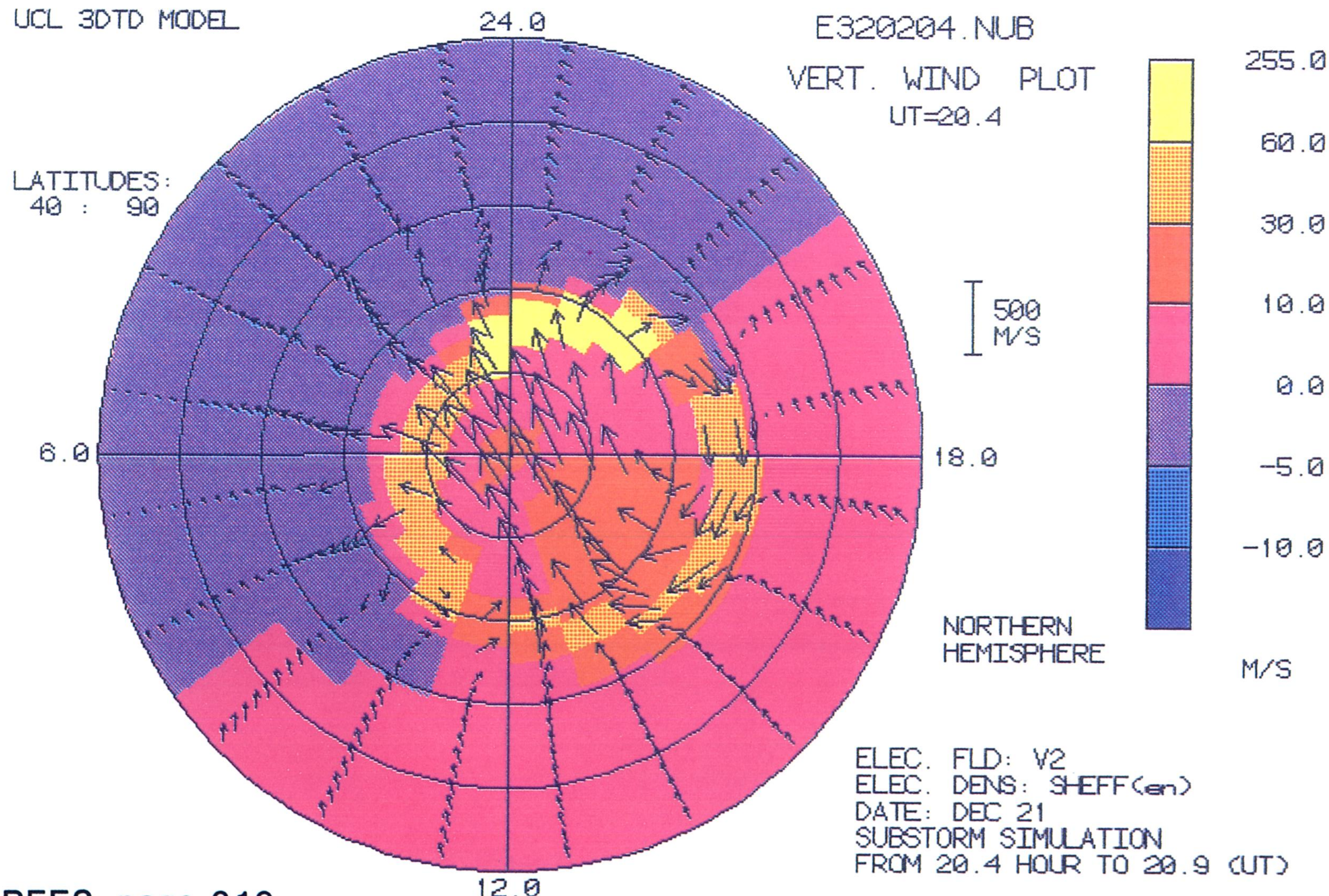

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Figure 8. Vertical and Horizontal wind distributions over the Northern Polar region during a geomagnetic substorm. The intense heating from particle and Joule heating effects in the midnight region of the auroral oval generate strong localized upward winds, and force an outward explosion of the thermosphere away from the region of the substorm and westward travelling surge. This Figure shows the onset phase, when the rapid upward vertical winds have been generated, but before the outward expansion has had time to develop.

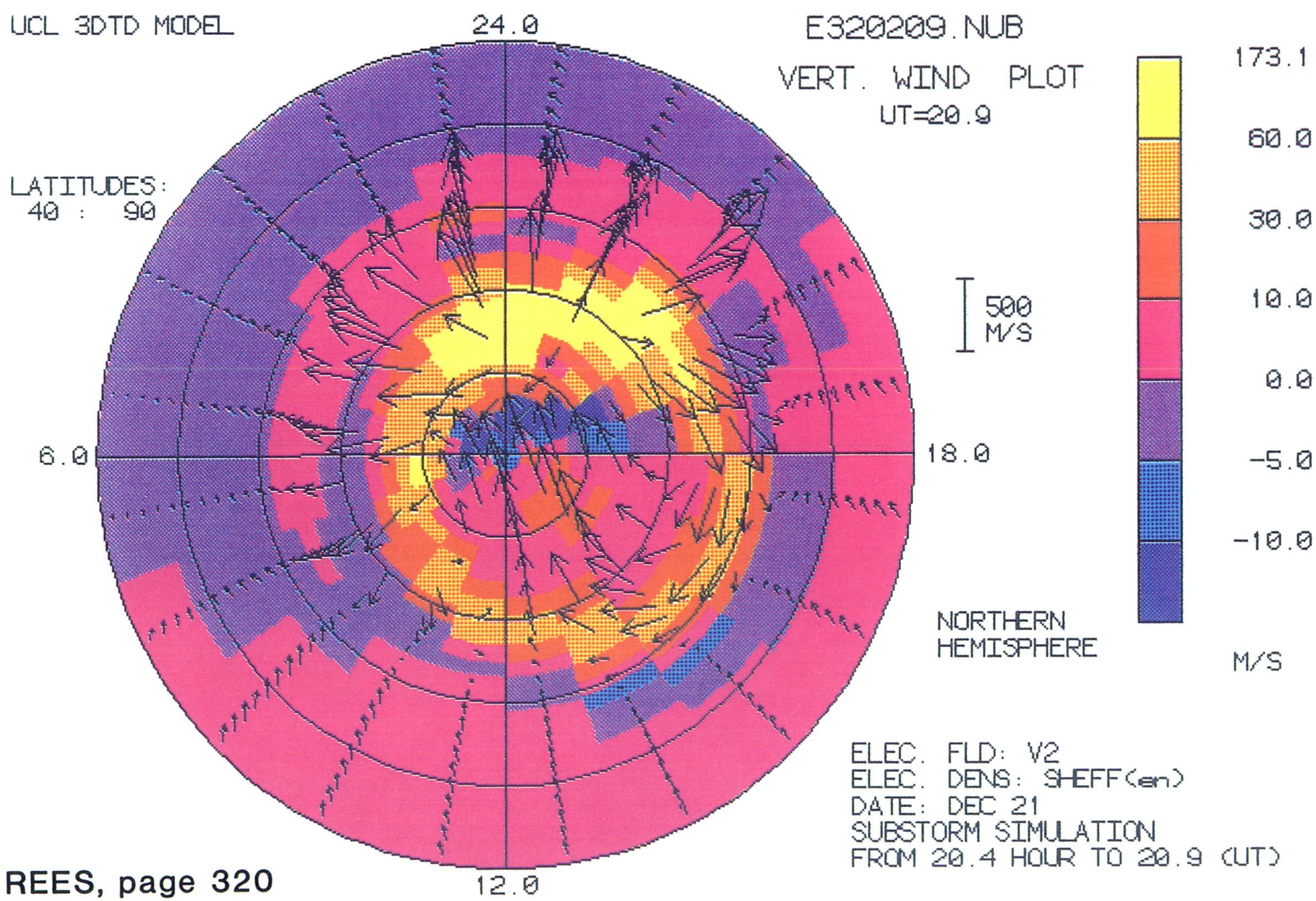

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Figure 9. Vertical and Horizontal wind distributions over the Northern Polar region for geomagnetic substorm conditions. The situation, simulated in Figure 8, has developed for a further 40 min, and now the outward explosion from the region of the substorm is clearly defined. At this stage, the gravity waves expanding from the auroral source region are well defined.

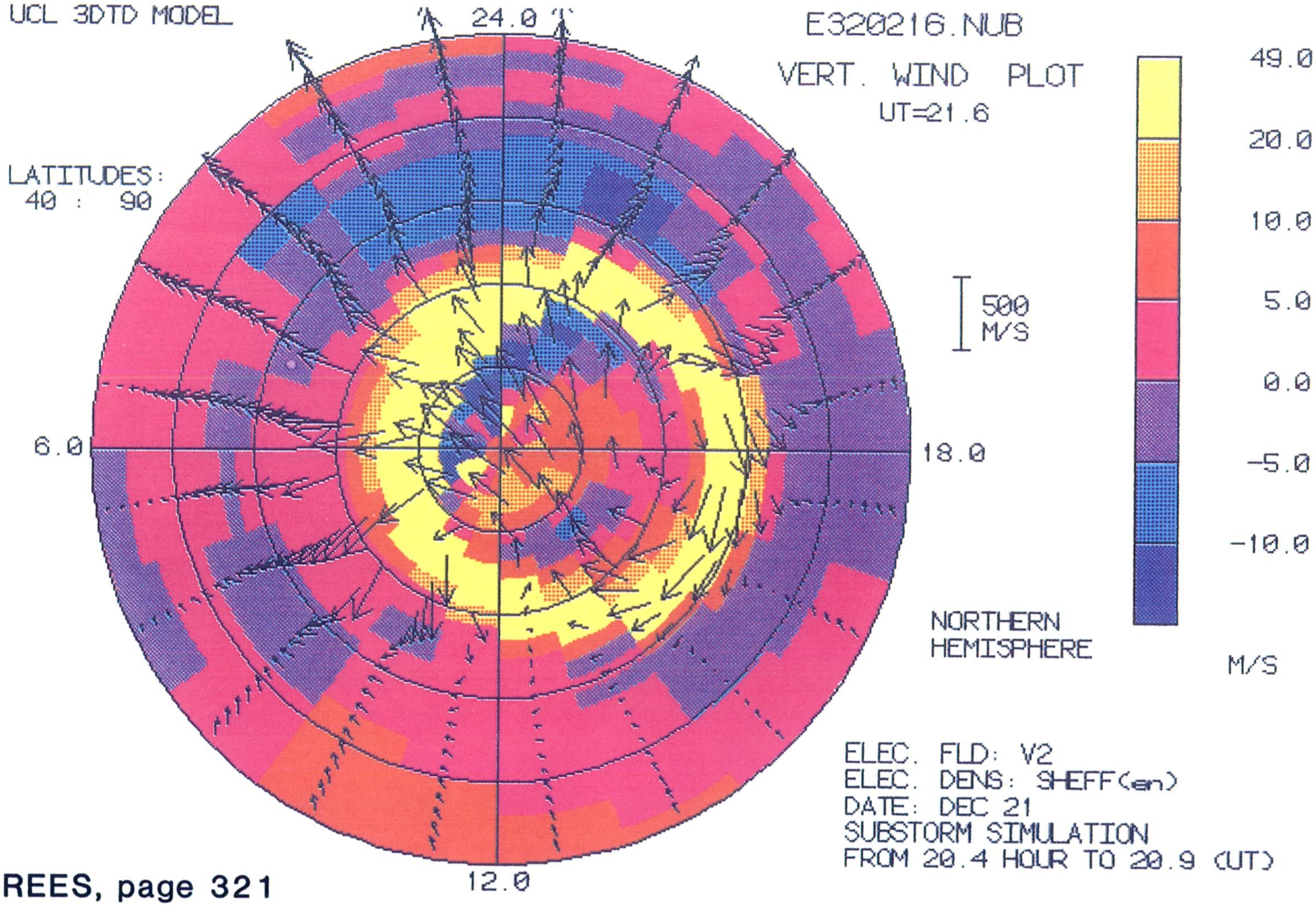

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Figure 10. Vertical and Horizontal wind distributions over the Northern Polar region for geomagnetic substorm conditions. This Figure shows the initial recovery phase after the disturbance. The outward explosion is no longer evident, and the peak upward winds have subsided. At lower latitudes, in the nightside part of the thermosphere, the rapid equatorward propagation of the gravity waves launched by the intense auroral disturbance can be seen.

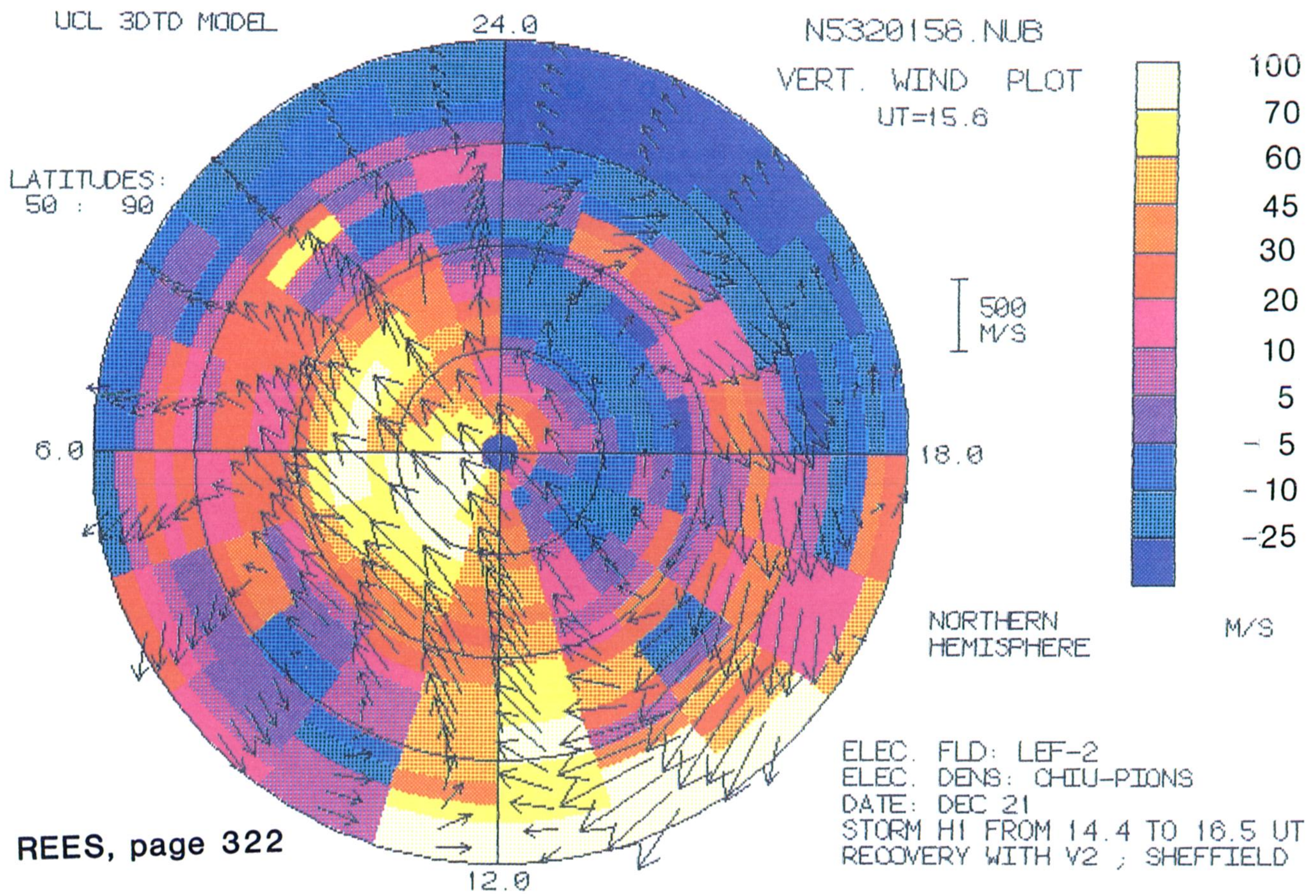

Figure 11. Vertical and horizontal wind distributions over the northern polar region for very disturbed geomagnetic conditions. This simulates the wind disturbances during a period when the IMF is extremely strong (20 nT), and with a large southward component. At such times, the auroral oval expands, and there may be a cross-cap potential of 120 - 150 kV. Km/sec winds are driven in the auroral oval and over the polar cap, and regions of systematic upward and downward wind flows exist within, and around the boundaries of the regions of intense geomagnetic energy and momentum inputs.